16:31:44 OCA PAD AMENDMENT - PROJECT HEADER INFORMATION 10/15/92

Active

Project #: E-25-M19 Cost share #: Rev #: 4
Center # : 10/24-6-R7359-0A0 Center shr #: OCA file #:
Work type : RES
Contract#: N61331-91-M-1332 Mod #: P00004 Document : PO
Prime #: Contract entity: GTRC

Subprojects ? : N CFDA: N/A
Main project #: PE #: 061331

Project unit: MECH ENGR Unit code: 02.010.126
Project director(s):
DICKERSON S L MECH ENGR (404)894-3255

Sponsor/division names: NAVY / NAVAL COASTAL SYS, FL
Sponsor/division codes: 103 / 001

Award period: 910925 to 921016 (performance) 921016 (reports)

Sponsor amount	New this change	Total to date
Contract value	0.00	6,182.00
Funded	0.00	6,182.00
Cost sharing amount		0.00

Does subcontracting plan apply ?: N

Title: OMNI-DIRECTIONAL VEHICLE ANALYSIS

PROJECT ADMINISTRATION DATA

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Security class (U,C,S,TS) : U ONR resident rep. is ACO (Y/N): N
Defense priority rating : DO-C9 GOVT supplemental sheet
Equipment title vests with: Sponsor GIT X

Administrative comments -
MOD #P00004 EXTENDS THE PERIOD OF PERFORMANCE AND THE DUE DATE FOR THE FINAL CDRL DELIVERY TO OCTOBER 16, 1992.

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SR-852

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

NOTICE OF PROJECT CLOSEOUT

Closeout Notice Date 04/20/93

Project No. E-25-M19 | Center No. 10/24-6-R7359-0A0

Project Director DICKERSON S L | School/Lab MECH ENGR

Sponsor NAVY/NAVAL COASTAL SYS, FL

Contract/Grant No. N61331-91-M-1332 | Contract Entity GTRC

Prime Contract No. ______

Title OMNI-DIRECTIONAL VEHICLE ANALYSIS

Effective Completion Date 921016 (Performance) 921016 (Reports)

Closeout Actions Required:	Y/N	Date Submitted
Final Invoice or Copy of Final Invoice	Y	
Final Report of Inventions and/or Subcontracts	N	
Government Property Inventory & Related Certificate	N	
Classified Material Certificate	N	
Release and Assignment	Y	
Other	N	

CommentsEFFECTIVE DATE 9-25-91. CONTRACT VALUE $6,182

Subproject Under Main Project No. ______

Continues Project No. ______

Distribution Required:

Project Director	Y
Administrative Network Representative	Y
GTRI Accounting/Grants and Contracts	Y
Procurement/Supply Services	Y
Research Property Managment	Y
Research Security Services	N
Reports Coordinator (OCA)	Y
GTRC	Y
Project File	Y
Other HARRY VANN-FMD	Y
FRED CAIN-OOD	Y

OMNI-DIRECTIONAL VEHICLE KINEMATIC AND DYNAMIC ANALYSIS AND INVESTIGATIONS

Georgia Institute of Technology
Technical Report
for
Naval Coastal Systems Center
Panama City, FL 32407-5000
Authority DI-MISC-80508
March 31, 1990

by

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TECHNICAL REPORT

ABSTRACT

This report reviews GFI (Government Furnished Information) and identifies approaches to improved ODV (Omni-Directional Vehicle) traction, dead reckoning, wheel design, vehicle performance and control. The GFI is abstracted and used to describe the state-of-the-art in the various technologies relative to motion control for an ODV. Alternative approaches to improved traction, dead-reckoning, wheel design, and vehicle performance and control are developed and discussed. Areas of insufficient knowledge have been identified.

GENERAL DISCUSSION - INTRODUCTION

The overriding concern in this report is the state of knowledge for construction of vehicles that might be used for material handling on ships. The technology of interest is the omni wheel, also called in the literature as the Mecanum wheel or Ilonator. The omni wheel is the only serious contender for a wheel that can propel a vehicle in any direction without a delay. In the literature, a vehicle that can be propelled in all of the three directions; longitudial, lateral, and roll; simultaneously and without delay is called holomonic or non-singular. Such a property provides potential for particularly good motion control when space is limited, time required for maneuvers needs to be short, or accuracy of small moves is required. Generally, the computer control is simpler also, since planning of motions is simpler. As an example, consider the problem of parallel parking of a car. A car cannot move directly into the desired position next to the curb, because it cannot move simultaneously in all three directions at any time. Rather, the driver must plan his motions, and take a rather roundabout path to arrive at the desired parking position. If the final position next to the curb is not adequate, large motions, forward and backward, are required to move over a small distance.

Because of this unique property of the omni wheel, there has been considerable interest in exploiting it. However, the paucity of operating experience and commercially available components has limited its use, and made it a topic of research. The omni wheel has potential shortcomings as well as the major advantage sited in the previous paragraph. The major concerns are in the areas of:

1. Wheel and vehicle kinematics
2. Wheel and vehicle dynamics
3. Control system architectures
4. Traction
5. Wheel slip detection and compensation
6. Dead-reckoning
7. Power consumption
8. Floor loading and wheel wear

Of these, only the last five can be thought of as *POTENTIAL* shortcomings. The first three deal with proper engineering of the vehicle control system. As indicated earlier, the control system design is in many ways simpler using omni wheels.

Item 4 through 6 are all related to wheel slip. No vehicle should be designed under the assumption that there will *NEVER* be wheel slip. Rather we design the vehicle and specify its operating conditions so wheel slip is typically minimized. If it does occur we must be able to recover gracefully.

Item 7 power consumption, relates to rolling resistance and the energy needed to accelerate and decelerate wheels. In some applications, power consumption is not important, but if a vehicle derives its power from batteries and has a high utilization, this is a concern.

Item 8, floor loading and tire wear, concerns the lifetime and maintenance of the floor and wheel. Again this may or may not be a concern, depending on the application.

In the following sections the various areas of technical concern are discussed and related to the literature.

SUMMARY OF VEHICLE KINEMATICS, DYNAMICS, AND CONTROL

The equations of motion in a kinematic and dynamic sense are well known. Much of the literature is devoted to these subjects. Most of the equations given are approximations, and are often not recognized as approximations. In today's environment, computing power is very inexpensive and reliable, so the exact equations of motion and the resulting control laws can include the slightly non-linear equations that accurately describe the kinematics of omni wheels.

The most standard references on the kinematics are included in several publications by Muir (Muir 86, 87, 88, 89) and earlier by Daniel (Daniel 84, 85). These kinematic equations are based on the approximation that the point of contact of the wheel on the floor is in the center of the wheel directly below the axis. That assumption leads to a simple set of equations relating the motion of the vehicle and the motion of the wheels.

$$\begin{bmatrix} \dot{\Theta}_1 \\ \dot{\Theta}_2 \\ \dot{\Theta}_3 \\ \dot{\Theta}_4 \end{bmatrix} = \frac{1}{r} \begin{bmatrix} 1 & -\cot(\varepsilon) & -(d + s\cot(\varepsilon)) \\ 1 & \cot(\varepsilon) & (d + s\cot(\varepsilon)) \\ 1 & \cot(\varepsilon) & -(d + s\cot(\varepsilon)) \\ 1 & -\cot(\varepsilon) & (d + s\cot(\varepsilon)) \end{bmatrix} \begin{bmatrix} v_x \\ v_y \\ \dot{\Psi} \end{bmatrix}$$

where

$\dot{\Theta}_i = i^{th}$ wheel rotation rate
$v_x, v_y, \dot{\Psi} =$ 3 vehicle velocities, including rotation
$r =$ wheel radius
$\varepsilon =$ roller angle (usually approximately 45°)
$d =$ width-wise distance from vehicle center to contact patch (direction of wheel axis)
$s =$ distance from vehicle center to contact patch lengthwise

Two German authored papers (Wampler 89, Graettinger 89) and a report from Georgia Tech (Lapin 90) point out that the kinematics is slightly more complex. As the point of contact between roller and floor move from one side of the wheel to the other, the relationship between motion of the vehicle and motion of the wheels is no longer linear. Rather the values of ε and d in the above equation vary with wheel position. Because the variation is a fixed function of wheel angle, any control program or dead-reckoning position estimator can include these non-linearities if high accuracy is required. Wheel position here refers to the angular position of the wheel in rotation relative to a standard position, for example, one roller directly below the wheel axle. Wheel position is readily measured with an optical encoder or a resolver on the wheel axle.

Control laws can be divided into two classes, resolved velocity and resolved acceleration. Both should work well. The best exposition on this subject is probably by Muir and Neuman(Muir 90). The essential feature of both methods is that a desired motion of the vehicle is converted to a desired motion of the wheels. In the case of resolved velocity, the motion of the wheels is described by an instantaneous desired velocity of each wheel. Each wheel has its own feedback control system which attempts to realize this velocity. In the case of resolved acceleration, each wheel has a desired instantaneous torque. The name resolved acceleration comes from the fact that acceleration and torque are proportional. Since electric motor torque is generally proportional to applied current, the local wheel feedback is part of the electric amplifier used to drive the motor.

Muir recommends resolved velocity for omni wheels, although he recommends resolved acceleration for the steered wheel case because of the greater difficulty of control for steered wheels. The author of this report, favors resolved acceleration for all cases because current computing power is not really limiting, and because it seems probable that slip detection and correction is easier in this case. Resolved acceleration is thought to also better handle non-linear effects not considered in Muir. However, in any case, both should work well.

In both cases, an outer loop is used to compare the vehicles actual motion with the desired motion and the individual wheel commands, velocity or torque, are updated at the sampling rate of the outer loop. The vehicles actual position must be determined in some manner. Most systems would use a combination of dead-reckoning and absolute measurements to estimate position. Dead-reckoning in general refers to basing the next estimate of position on the last estimate of position and some measured relative motion during the interval of time between estimates. Often the relative motion measurement is based on the wheel motion itself, that is, how much did each wheel turn. Dead-reckoning in this case is based on the assumption of well known rolling geometry and no wheel slip. Rolling geometry refers both to wheel geometry and surface geometry, usually flat. Because wheel slip and dead-reckoning are important we turn to that next.

SUMMARY OF TRACTION, WHEEL SLIP, AND DEAD-RECKONING

Dead-reckoning refers to the ability to know approximately the current position of a vehicle, based on a knowledge of a previous position, and a measurement of the motion of the vehicle in between. Essentially, one is integrating the equations of motion for dead-reckoning. No vehicle can depend exclusively on dead-reckoning because the error in estimated position will continue to grow. However, the use of dead-reckoning is essential if no external measurement of position is available for a period of time. Even if external measurement of position is available, dead-reckoning allows a better estimate of position because it effectively allows the averaging over many external measurements. This averaging process is usually some form of a Kalman filter although it may not go by that name.

The author sees no indication in the literature, that dead-reckoning is more or less practical for omni wheels relative to conventional wheels. It is pointed out however, that many standard computer controlled vehicles, for example from TRC, Cybermotion, and Denning, have good dead reckoning capability but depend very much on operating on smooth, clean floors. Furthermore, since all of these have no redundancy in their propulsion systems, they have no direct way of measuring wheel slip. Hence, they do not know if errors have occurred and have no way of resolving errors if they are detected.

A 4 wheel omni vehicle, particularly one using resolved acceleration, can detect slippage, and with the assumption that only one wheel is slipping can correct for slippage. The correction includes basing dead-reckoning on the remaining 3 wheels, and on reducing the load on the slipping wheel (and all wheels if necessary) in order to stop the slippage. This process is described in(Lapin 90).

There is a complication with omni wheels for cases where very accurate dead-reckoning is desired. That is that the simple linear model of kinematics has local errors. This can be readily compensated for if each wheel has a resolver or encoder on each wheel. That is, we must know the wheel position in order to integrate accurately the equations of motion. Only wheel position must be measured, because incremental position is used in well designed numerical methods for dead reckoning. Velocity is not used directly.

Traction itself, the ability to provide a force in any of the three directions is a major topic of concern with omni wheeled vehicles. When compared to a conventionally wheeled vehicle, the omni vehicle may have more or less traction depending on the design of the conventional vehicle and whether traction is defined for a stationary or moving vehicle. Based on the wheel itself, compared with conventional wheels, the omni vehicle has as low as 50% of the traction in some directions. However, this understates the typical true traction. If a conventional vehicle has only 2 of 4 wheels driven, or only 50% of its load on the driven wheels, then traction is likely to favor the omni vehicle. If further, the drive of the wheels is through a differential, then significant reduction in true traction is likely since the first wheel to spin determines traction. Experimental studies, summarized and tabulated by Blaisdell (Blaisdell 91), show that traction for an omni vehicle is good relative to realistic alternatives, particularly for adverse surface conditions.

His results which seem to be the best compilation available for ice and snow conditions compare omni wheels, non-pneumatic treadless tires, bias highway tires and radial all-season tires. Three surface conditions are compared: fresh snow on a frozen grass covered field, hard-packed snow on a road, and ice on an ice-rink. The traction coefficient, comparable to the coefficient of friction, is reported to be lowest for ice, and greatest for snow. Based on pure pulling power in the forward direction, the omni wheel is best when conditions are worst. The table below summarizes the results. The numbers in the table can be thought of as the coefficient of friction.

	Ice	Hard Snow	Fresh Snow
Omni wheel	0.05	0.21	0.33
Nonpneumatic treadless tire	0.011	NA	NA
Bias highway tire	NA	NA	0.44
Radial all-season tire	NA	0.25	0.48

Because these tests were done with an omni wheeled vehicle with a 45 degree roller angle, the simplest model based on a static coefficient of friction would result in the omni wheel having a traction coefficient of 71% of that of a conventional wheel. However, it does better than that in every case except for the radial tire fresh snow case. This is believed to be the case because the omni wheel presents a moving point of contact as the wheel rotates. This causes a continuos climbing effect which seems to increase friction.

SUMMARY OF POWER CONSUMPTION

Power consumption in this case is a direct result of what is commonly called rolling resistance. A "typical" value of rolling resistance is 2% of load for a pneumatic tire. That is, if the load on a wheel is 100 Newtons (22 pounds), then the effort to move the wheel forward is 2 newtons (0.45 pounds).

Daniel on page 6 (Daniel 84) used 3.2% but had no real basis for this number. In an experimental report by Daniel and Krogh (Daniel 85), he reported that "for pure rotation the chair required a minimum PWM of 8% of the duty cycle to each wheel." However, not enough additional information is given to convert this to a rolling resistance coefficient. He does give an experimental result that the sideways motion, has approximately 4 times the static rolling resistance of forward motion. FMC (FMC 89) seems to give a ratio of between 2.7 (rolling resistance only) and 8 (rolling resistance plus bearing friction) for the ratio of sideways resistance to forward resistance. That is, if the bearings in the rollers are neglected the power consumption to overcome rolling resistance in the lateral or sideways direction is 270% of the power required to go straight forward or backward. FMC estimated that this would increase to 800% when roller bearing resistance is included. Discussions about the FMC report indicate, and the author agrees that bearing friction was greatly overstated relative to what could be expected in a good anti-friction design of the rollers. The implied rolling resistance from the FMC report in the forward direction is about 1.3% of load, a reasonable number.

All indications are that in forward motion, an omni wheel and a conventional wheel are comparable. The actual value of rolling resistance will depend mostly on the hardness of the wheel and the hardness of the supporting surface. Soft, low hardness wheels, require that the surface of the wheel be restrained from "stretching" as the wheel comes in contact. This is usually accomplished by embedding a stiff fabric just below the surface as in a radial tire.

If an omni wheel has a lateral or sideways component of motion, then the rollers themselves must turn. This typically leads to greater rolling resistance. In the opinion of the author, this greater resistance is due to the need to accelerate the roller, the small effective radius of the roller relative to the wheel itself, and the bearing friction in the roller. However, the latter, by design can be made quite small, and all three are reduced by larger diameter rollers.

SUMMARY OF FLOOR LOADING AND WHEEL WEAR

Floor loading here is taken to be the pressure in the contact patch between the roller and floor. With a pneumatic tire at low speeds this can be taken as the inflation pressure, which for motor vehicles is typically in the 25 to 120 psi range, although aircraft tires are frequently inflated to 500 psi*. Their is very little information available on typical floor loadings for omni wheels. Mecanum Co. (MECANUM) rates some of its wheels for loads up to 940 psi. This may seem high, but should not be a problem for steel or concrete floors. This high floor loading is for a wheel with a rated load of 5500 pounds.

Wheel wear is a subject that seems to be entirely missing in the literature. Wear is a difficult subject under the best of circumstances. Tribologists measure wear in terms of a wear constant which is expressed by

Wear constant, $K = d\,H/(D\,P)$

where:

- D is sliding distance (implies some slip or relative motion),
- H is hardness measured in pressure terms (typically the yield strength in compression)
- P is contact pressure, and
- d is wear amount measured as thickness of material removed.

Clearly K is unitless. Typical values of K are between 10^{-4} and 10^{-12}, a very wide range.

Their appears to be considerable literature on pneumatic tire wear and on the wear of elastomers. Unfortunately, everyone agrees that wear in a real situation is quite unpredictable. Although most agree that relative motion, that is sliding, is the main cause of wear, part of the unpredictability is in knowing the amount of sliding. An article (Grosch92) that seems to provide a good review of many studies, indicates that wear is a non-linear function of contact pressure, with wear rates increasing more rapidly than pressure. That is,

$$\left(\frac{d}{do}\right) = \left(\frac{p}{po}\right)^n$$

where n is between 1.4 and 2.5. The same article indicates that natural rubber has better wear characteristics than butyl rubber. Another article (Baker89), also favored "natural rubber-rich" compounds over the "best synthetic treads" for reduced wear. The rubber-rich compounds also exhibited lower rolling resistance.

In pure rolling contact D is zero, implying no wear. But pneumatic tires wear, radial less than bias ply. Most of the wear is presumed to be due to the expansion and contraction of the contact patch during rolling. This effect is minimized in radial tires by the greater stiffening of the plys under the rubber.

*Naval Air Station, Atlanta, gave the standard pressure for an A7 on carrier duty as 325 psi.

In the case of omni wheels, several qualitative comments are offered.

1. The total available wear surface is relatively large because the effective surface is that of the rollers, not that of the outer surface of a wheel as in a conventional tire. This should reduce wear in the sense of reduced d.

2. The fact that omni wheels do not "turn" in order to change direction, reduces sliding. This could be significant in situations requiring frequent changes in direction.

3. The hardness in the above formula is not the same as stiffness or the modulus of elasticity. That is, an elastomer with a low modulus of elasticity, could be relatively hard because of its high strength. Therefore, it is not clear that a stiff material will reduce wear. If a stiffer elastomer reduces wear, it is more likely because of reduced D, rather than greater H.

DESIGN TRADE-OFFS

An attempt is made here to indicate design considerations, particularly as they relate to traction and dead-reckoning.

Indications are that traction with an omni-wheeled vehicle is as good or better than that for a conventional wheeled vehicle under adverse conditions (Blaisdell 91) in the sense of drawbar pull. In the case of flat dry floors, where the traction is governed by the coefficient of friction alone and not any "tread" action, then it is clear that a conventional wheeled vehicle WITH ALL WHEELS POWERED will have a greater drawbar pull.

However, drawbar pull in one direction is not the only consideration in traction. At least three operating conditions should be considered:

1. vehicle stationary and wheels locked,
2. straight line motion, and
3. dynamic motion where maneuvers are in progress.

For the case a stationary vehicle with wheels locked, it is clear that on a smooth surface a omni-wheeled vehicle has less holding power than a conventional wheeled vehicle. The most adverse direction to slide is in the direction perpendicular to a set of roller axis, generally 45 degrees from the forward direction. This effect of rollers turning would be much less if the wheel were in mud or deep snow, where the rollers would engage the material, rather than simply roll. Of course this difference in static holding power could be overcome by locking the rollers as well as the wheel.

For the case of a vehicle in straight line motion the drawbar case holds. However, as with the test by (Blaisdell 91) the direction of straight line motion is important. A vehicle moving in the 45 degree direction as indicated in the previous paragraph will generally have less drawbar pull.

For the case of dynamic maneuvers, the omni-wheeled vehicle is likely to do very well. Although no definitive tests are available, on either the omni-wheeled case or the conventional wheel case, logic and antidotal information indicates that the omni-wheel should do very well by comparison. The fundamental reason for the increased relative traction is that the omni-wheel itself does not need to change direction in order to move in a different direction. Thus there is no scuffing (or rotation of the contact patch) as the vehicle changes direction. A rotating contact patch has greatly reduced traction because all but one point in the patch is sliding. An easy illustration of this is a toy spinning top on a plate. Even though the patch is extremely small, which means sliding velocity is small, the top will always drift, usually in the downhill direction. But sometimes it will drift in other directions because of the complexity of the interaction with the surface and contact patch.

Now consider what measures in the design might be taken to maximize traction and minimize wear.

1. The ability to lock the rollers should allow greater holding power when stationary and perhaps could be used in straight forward/backward motion as well. The vehicle would then have been converted to a four wheel drive vehicle with all wheels powered, which might be useful in some situations. Roller locking should not be difficult to implement.

2. The load on all wheels should be kept approximately equal. A wheel with lighter load is likely to slip first. Equal load on the wheels generally requires that the center of gravity of the total load be at the center of the wheel pattern and that the wheels have a spring loaded suspension. The suspension is needed to accommodate irregularities in the floor. If loads were uneven, an advanced resolved acceleration algorithm could use this information in commanding motor torques.

3. In an extreme case, all rollers could be powered as well as all wheels. A scheme for this was proposed in (Lapin 90). In this case, the omni-wheel is powered to move in any direction all by itself. Only two wheels need to be in contact for complete motion control. However, the construction of the wheel is more complex and two motors rather than one are required at each wheel. (Of course, an all wheels steered systems also require two motors per wheel.)

4. Slip detection and compensation can be used to minimize sliding between the rollers and the floor. This increases traction. The increase traction is the result of static friction usually exceeding dynamic friction. This is the principle behind anti-lock brake systems. It applies equally well to braking or accelerating. Of course, slip detection and compensation is vital for dead reckoning calculations if dead-reckoning is to be used in a situation where slip could occur. Schemes for slip detection and compensation are given by (Lapin 90, Graettinger 89, Muir 86/87/88, Waldron 85, Wampfler 89)

5. Treads on rollers could be used. No omni wheels with treads are known. Treads can increase traction by engaging the surface material and by prevention of hydra-planing. Hydra-planing is unlikely at the velocities of ship board vehicles. It appears to the author that treads could also decrease wear by reducing the local slippage due to contact patch expansion and contraction as the patch moves.

6. A fabric stiffening of the roller surface as in a radial tire, might increase traction and reduce wear. Both of these benefits come from the reduced expansion and contraction of the contact patch, and hence reduced local slippage of the roller relative to the floor.

Now turn to the design considerations in dead-reckoning. The first question is whether or not to depend on dead-reckoning at all.

Most research vehicles and commercial automated guided vehicles (AGV) depend on dead-reckoning to some extent, however, none depend on dead-reckoning entirely. Real working vehicles, for example the TRC vehicle for hospital and handicapped assistance, and the Caterpillar industrial AGV do use wheel rotations to "smooth" the data coming from absolute measurements of position. However, they are not dependent on wheel rotation measurements over any significant distance. Furthermore, the environment, particularly for the TRC vehicle is usually very good, so wheel slip can be prevented. Some of the research vehicles, particularly the Cybermotion vehicle and the Denning vehicle have been used over rather long paths using only dead-reckoning with rather good results. BUT, this has been achieved in laboratories, with light and constant payloads, with lightly loaded wheels that have a very small contact patch.

There is current work on various learning schemes to help compensate for vehicle loading, tire wear, and changes in vehicle parameters to make dead-reckoning more accurate. Remember that tire wear, vehicle loading, floor slope, acceleration, and deceleration, all influence the relationship between wheel motion and vehicle motion. Since dead-reckoning uses wheel motion to predict vehicle motion, this relationship must be known with sufficient precision.

As a bottom line, the author suggests that shipboard vehicles DO NOT DEPEND on dead-reckoning based on wheel motions for any purposes except for cross checking, data smoothing, and small motions. For example, cross checking could be used to compare implied motion with measured motion and help in the detection of wheel slip and or suggest other unexpected problems. When absolute measurements are made repeatedly, and they often can be done tens or hundreds of times a second with electronic devices, the motion of the wheels can be used to fit the data. This is the Kalman filter idea. Very small motions, for example moving 0.2 inch in a particular direction, may best be made using wheel rotations because other sensors may not have sufficient resolution or bandwidth.

All of the foregoing aside, assume that dead-reckoning is to be made as accurate as possible. First the author sees no reason why omni-wheels should not be able to do as well as conventional wheels for comparable precision in wheel construction. There is the need to prevent slip, or if there is slip on one wheel be able to detect it and use the data from the non-slipping wheels. There is also the need to compensate for the moving contact point as suggested earlier. This would have been a problem until the last ten years when very compact, capable micro-computers made this compensation very feasible. An encoder, or resolver on each wheel will be required in any case. The micro-computer integrates the non-linear equations of motion.

Finally, dead-reckoning with an omni-wheel may be better than with a conventional steered wheel because of the holomonic characteristics of the wheel.

No slip is required to change directions. In a steered wheel, the contact patch is rotating while turning. This leads to uncertainty as to the exact instantaneous stationary point in the contact patch, particularly if the wheel is experiencing a horizontal load. The effect may be significant in cases of considerable maneuvering and for heavy vehicles where the contact patch is large.

RESEARCH AND DEVELOPMENT NEEDS

The omni wheel as a component of a ship board vehicle shows a great deal of promise. No competing technology can provide comparable maneuverability, likely to be of significance in the crowded shipboard environment. Because of its highly maneuverable characteristics it reduces automatic control difficulties associated with non-holomonic or singular suspension systems, and should provide greater accuracy of motion. However, there are some research and development issues unique to the omni wheel that might be addressed. Any improvement of this technology, would have significant civil sector applications as well. The automated guided vehicle industry may be on the verge of becoming a high-tech, growth industry.

In what follows, those research and development issues common to all automated guided vehicles are not addressed, primarily the issue of being able to know what motion is required, and the location of the vehicle. These fundamental problems of planning and sensing have been addressed in literally hundreds of research efforts. The author does suggest that accurate dead-reckoning based on wheel rotations not be essential to any scheme regardless of wheel design.

Roller Design

Although there has been a company in the omni wheel manufacture business for many years, Mecanum AB in Sweden, it does not appear that they have the resources or knowledge to provide off-the-shelf wheels of the technology level that would be desirable for military applications and be able to describe the wheels characteristics adequately. Rolling resistance, wear, and traction are the unknowns and the items needing "optimization." It appears to the author that a fabric-backed, treaded roller should be considered, the fabrication of such requiring some development work. Experimental tests would be part of such a development effort.

Low-Level Control Law for Slip Detection and Compensation

An anti-skid propulsion system is desirable from the standpoint of optimizing performance, minimizing roller wear, and maximizing the dead-reckoning capabilities. This should be relatively straight forward, but an R and D project based on an existing vehicle could be devised to verify any results. (Lapin 90, Graettinger 89,Muir 86/87/88, Waldron 85,Wampfler 89) all provide suggestions on anti-skid methods.

Roller Braking and/or Driving

There appear to be advantages of roller braking that could be achieved by relatively simple modifications to wheel design. These would probably be based on internal, pneumatic or hydraulically actuated brakes. Many of the advantages could be achieved with an on/off device rather than continuously variable braking. In particular, braking could be used for a stationary vehicle, or in the case of forward motion in some adverse traction conditions. In a pinch it would be nice to be able to switch to locked rollers.

Driven rollers presents a more costly alternative but could be justified if "cost were no object" or for a mass produced wheel. This would provide the ultimate in performance.

BIBLIOGRAPHY, GFI

(Agullo 87), J. Agullo, S. Cardona, and J. Vivancos, "Kinematics of Vehicles with Directional Sliding Wheels," Mechanicsm and Machine Theory, Vol 22, No. 4, 1987, pp. 295-301

A rather low level look based on the simplest if models. Uses "sliding wheels" as term for for omni wheels.

(Bird 88), J. D. Bird and J. A. Conte, Omni Directional Demonstration Vehicle, Naval Coastal Systems Center report no. NCSC 3320/001-88, September 1988, 17 pages.

This report describes the conversion of an Cadillac Gage manufactured omni vehicle to a demonstration vehicle. The original vehicle was powered by a gasoline engine and carried a driver. The modified vehicle was battery powered and used a joystick control on a tether.

Also described are some traction tests on ice in an ice rink. These tests showed the omni wheels to be superior in traction to the hard rubber wheels of a forklift truck. Data is given on the drawbar pull in various directions while on ice.

kinematics (Yes), dynamics (No), control (Yes), wheel slip (Yes), dead-reckoning(No), traction (Yes), power consumption (Some)

(Blackwell 91), M. Blackwell, The URANUS Mobile Robot, Report no. CMU-RI-TR-91-06, Carnegie Mellon Univ., Robotics Institute, 1991, 25 pages.

This document gives the electro-mechanical details of the subject vehicle, which has been developed over a number of years. The introduction gives a history of CMU wheeled mobile robots, and is a testimony to the advantages they experienced using the Mecanum or omni wheels. Other than the wheels, interesting features of the design are brushless, permanent magnet drive motors (rather advanced when chosen), the wheels direct from Mecanum of Sweden, and the suspension system that keeps all wheels in contact with the ground. They point out that this is important for motion control and dead reckoning.

(Blaisdell 91), G. L. Blaisdell, "Performance of an Omnidirectional Wheel on Snow and Ice," Naval Engineers Journal, Jan. 1991, pp. 34-41.

This paper is unusual. It presents experimental data on traction of omni wheels compared to more conventional wheels. The tests, done by the US Army appear unbiased. In straight drawbar tests, the omni-wheel was evaluated as having about

85% of the traction of a radial all season pneumatic tire on hard packed snow; 68% of that of the same type of tire on fresh snow; 74% of a bias ply pneumatic tire on fresh snow; and 436% of a hard rubber fork lift truck tire on prepared ice. (A straight coefficient of friction argument would have resulted in 71% for every case) Some data for omni wheels is also presented on drawbar pull for sideways and diagonal directions.

kinematics (No), dynamics (No), control (No), wheel slip (Yes), dead-reckoning(No), traction (Yes), power consumption (No)

(CMU 85), various authors, Autonomous Mobile Robots, Annual Report -1985, Report No. CMU-RI-MRL 86-1, Carnegie Mellon Univ., Robotics Institute, 1986, 158 pages.

The first few pages of this report provide an overview from the staff of their work on autonomous vehicles. Most notable, was the conclusion that the omni-wheel or Mecanum wheel, "is the most practical omnidirectional system." This conclusion was reached after building 3 different vehicles, each with a different wheel arrangement. The omni wheel has since become the wheel of choice at CMU. They also note that the wheel has good bump and soft ground handling ability in the forward direction.

A separate section of the report by Gregg Podnar describes the URANUS mobile robot, the 4 wheel omni vehicle. This vehicle uses brushless DC motors and a trailing-arm arrangement for the wheel suspension. The vehicle is capable of 4 hours of battery operation at normal loads. The vehicle construction is very similar, but smaller in scale to the vehicle currently under construction for the Navy.

A final section by Hans Moravec, entitled Robots the Rove, deals with very general concepts of the meaning of mobility in animals and machines. It makes very interesting reading.

In addition there are parts by Muir, Neuman, and Shin, very similar to (Muir 86) and (Muir 87).

kinematics (Yes), dynamics (Yes), control (Yes), wheel slip (Some), dead-reckoning(Yes), traction (Some), power consumption (Some)

(Daniel 84), D J. Daniel, Analysis, Design, and Implementation of Microprocessor Control for a Mobile Platform, MS thesis at Carnegie-Mellon Univ., August 1984, 74 pages.

This is the original description of the controller used in (Daniel 85) and (Feng 89), a Motorola 68000 based control of an 4 wheeled OMNI vehicle. A notable feature is a discussion and analysis of rolling resistance and power consumption. PWM motor control is described in detail.

kinematics (Yes), dynamics (No), control (Yes), wheel slip (No), dead-reckoning(No), traction (No), power consumption (Yes)

(Daniel 85), D. J. Daniel, B. H. Krogh, and M. B. Friedman, "Kinematics and Open-Loop Control of an Ilonator-Based Mobil Platform," ??IEEE, 1985, pp. 346-351.

This paper concerns the same vehicle as (Feng 89). Two interesting experimental observations are (1) that the relative power (actually torque) required to cause motion was much greater to translate sideways than forward because of the roller bearing friction, and (2) that for constant wheel velocities the vehicle moves in a circle. Both of these effects are fairly obvious, but the obvious is often overlooked.

kinematics (Yes), dynamics (No), control (No), wheel slip (No), dead-reckoning(No), traction (No), power consumption (Some)

(EGG 89), no author, Stability and Skidding Analysis for the Omni Directional Vehicle, final report under NCSC contract no. N61331-89-M-4401, Nov. 1989, 22 pages.

The report gives equations and documents a computer program to predict the minimum coefficient of friction required so that no wheel will slip when on the deck of a ship. The variables are geometry and weight distribution of the vehicle and the effective acceleration of the ship's deck. The essential result is that an omni vehicle would require 2+ times the coefficient of friction of a conventional vehicle with all wheels locked. As pointed out in the last section of the report this result is misleading for a number of reasons including:

1. vehicles do not operate with wheels locked, rather we are more interested in traction when in motion,

2. when in motion, an omni-wheeled vehicle is able to respond more quickly to skidding, and

3. most conventionally wheeled vehicles, even if 4 wheel drive, propel the wheels through differential drive systems. These drives increase slipping when under power.

It is pointed out that brakes could be provided for rollers in those cases where a locked wheel anti-skid was needed.

kinematics (Yes), dynamics (Yes), control (No), wheel slip (Yes), dead-reckoning(No), traction (Yes), power consumption (No)

(Everett 89), H.R. Everett and G. A. Gilbreath, ROBART II, A Robotic Security Testbed, NOSC Tech. Doc. No. 1450 (AD-A208 399), January 1989, 62 pages plus addendices.

This report describes in some detail a battery powered security vehicle. The vehicle is characterized by a large number of sensors: temperature, humidity, barometric pressure, ambient light, noise, toxic gases, smoke, fire, infrared body heat, optical motion, ultrasonic motion, microwave motion, video motion, and vibration. Taken together these sensors detect intruders and measure the location of the vehicle. The suspension/propulsion system consists of two fixed driven wheels and two castor wheels. This allows powered turning to any angle and forward and backward motion.

The vehicle has a high level path planner, currently off-board, that can rely on a stored map and sensed obstacles to generate a feasible path between arbitrary points.

kinematics (No), dynamics (No), control (Yes), wheel slip (No), dead-reckoning(Yes), traction (No), power consumption (No)

(Feng 89), D. Feng, M. B. Friedman, and B. H. Krogh, "The Servo-Control System for an Omnidirectional Mobil Robot," ??IEEE, 1989, pp. 1566-1571.
(probably IEEE conference on robotics and automation)

This paper provides an example of a real control system of an omni vehicle. It uses a simple resolved wheel velocity controller. Most of the paper deals with the electronic hardware, micro-processor, encoders, motors, used for the control. Experimental results are good. They experienced no slip at less than 1 m/sec.^2.

kinematics (Yes), dynamics (No), control (Yes), wheel slip (Some), dead-reckoning(Some), traction (Some), power consumption (No)

(FMC 89), T. H. Chung of FMC, Omni-Wheel Design/Analysis Model Review, Draft report No. MTM 293-89, November 20, 1989, 14 pages.

The interesting part of this report is the analysis of power consumption for an omni wheel. It's analysis of rolling resistance appears to be approximately correct. The analysis of omni wheel internal friction appears to use very high friction roller bearings which gives misleading results.

kinematics (Some), dynamics (No), control (No), wheel slip (No), dead-reckoning(No), traction (Some), power consumption (Yes)

(Graettinger 89), T. J. Graettinger and B. H. Krogh, " Evaluation and Time-Scaling of Trajectories for Wheeled Mobile Robots," Journal of Dynamic Systems, Measurement, and Control, ASME, Vol. 111, June 1989, pp. 222-231,

The ability of a conventionally steered vehicle (CSV) to follow a prescribed path is analyzed. Both kinematic constraints imposed by limited steering angles, and dynamic constraints imposed by tractive limits are examined. The path must be modified if the kinematic constraints are not met. The time scale can be changed (vehicle slowed down) if the dynamic constraints are not met. A two-directional friction force constraint is used to account for possible differences in the friction coefficient in the lateral and longitudinal directions.

kinematics (Yes), dynamics (Yes), control (No), wheel slip (Some), dead-reckoning(No), traction (No), power consumption (No)

(Harmon 88), S. Y. Harmon, "A Report on the NATO Workshop on Mobile Robot Implementation," IEEE??, 1988, pp. 604-610.

The workshop was in October 1987. The workshop and this paper concentrated on identifying the limitations in the technology needed to support mobil robots. In many ways it is a pessimistic presentation, in the reviewers opinion too pessimistic. In the conclusion it is stated that "sensing, real-time computation, vehicle modeling, human interfaces and communications are major limitations to the admissible complexity and bandwidth of a a mobile robot's task environment." (emphasis added) The paper may be proposing that tasks be limited and in environments favorable to vehicle use.

kinematics (No), dynamics (No), control (No), wheel slip (No), dead-reckoning(No), traction (No), power consumption (No)

(Ilon 86), B. E. Ilon, Device for Exploiting the Maximum Drive Unit Torque of the Drives of Vehicles or Conveyors, US Patent No. 4598782, July 8, 1986

The patent seems to tell of an analog controller of torques at the four motors of a vehicle. It would appear to be an out of date method, as digital controllers would do better.

(Lapin 90), B. D. Lapin, S. L. Dickerson, and W. D. Holcombe, Omni-Directional Vehicle Survey and Analysis, Georgia Tech's Material Handling Research Center report no. B-10-632, Feb. 1990, 49 pages + 9 appendices.

This report compares all wheel steered and omni wheel as alternative 3 degree of freedom vehicle designs and concludes that omni wheel is superior for most applications. Also examined are the space and time savings associated with 3 DOF motions relative to 2 DOF. A compact and computer coded geometric design of wheels is provided. The equations of motion including the non-linear effects of the wheels are developed, although these are not in closed form.

kinematics (Yes), dynamics (Yes), control (Yes), wheel slip (Some), dead-reckoning(Some), traction (Some), power consumption (Some)

(Muir 86), P. F. Muir, and C. P. Newman, "Kinematic Modeling of Wheeled Mobil Robots," Carnegie-Mellon Univ., Robotics Inst. report no. CMU-RI-TR-86-12, June 1986, 126 pages.

This is an early version of (Muir 88), and concentrates on the kinematics only. Some concentration on wheel slip detection. The report does not use the resolved rate and resolved acceleration control strategies but does have a similar method of detecting wheel slip. Wheel slip is detected by a discrepancy in wheel velocity as in (Muir 88).

kinematics (Yes), dynamics (No), control (Some), wheel slip (Some), dead-reckoning(Yes), traction (No), power consumption (No)

(Muir 87), P. F. Muir, and C. P. Newman, "Kinematic Modeling and Feedback Control of an Omnidirectional Wheeled Mobile Robot," ??IEEE, 1987, pp. 1772-1778.

This is an early version of (Muir 88), and concentrates on the kinematics only. Some concentration on wheel slip detection. All control and sensing is based on wheel velocity.

kinematics (Yes), dynamics (No), control (Some), wheel slip (Some), dead-reckoning(Yes), traction (No), power consumption (No)

(Muir 88), P. F. Muir, Modeling and Control of Wheeled Mobile Robots, Ph.D. thesis, Carnegie-Mellon Univ., August 1988, 343 pages.

A comprehensive study of the kinematics and dynamics of wheeled vehicles. Wheeled vehicles are those that are propelled by wheels intended to have a single point of rolling contact at each wheel. Two vehicles are examined in detail, Uranus which has 4 omni wheels and 3 DOF, and Bicsun-Bicas which has two fixed independently powered wheels, 2 castor wheels, and only 2 DOF.

Both resolved rate and resolved acceleration servo-control are examined. The mathematical formulations for the resolving in both forward and reverse directions are provided. When used for control, resolved rate is largely a kinematic based control method, while resolved acceleration, includes the dynamic terms. Based on simulation, Muir concludes that rate is adequate for Uranus while acceleration is needed for Bicsun-Bicas.

This is a primary reference for the mathematics of resolving desired motion into wheel velocities and accelerations and the inverse for dead-reckoning. Although the subjects of friction and power loss are treated in the modeling of motion, adequate models are not given. The model of the omni wheel is of the ideal, fixed-contact-point type. A method of detection of wheel slip is provided.

Approximately 140 references are cited in the bibliography.

kinematics (Yes), dynamics (Yes), control (Yes), wheel slip (Some), dead-reckoning(Yes), traction (No), power consumption (No)

(Muir 90), P. F. Muir and C. P. Neuman, "Resolved Motion Rate and Resolved Acceleration Servo-Control of Wheeled Mobil Robots," ??IEEE, 1990, pp. 1133-1140.

This is a summary of the thesis (Muir 88) which provides a clear exposition of "resolved motion rate" and "resolved acceleration" WMR servo-control. These are the two most likely architectures for the low-level control of a vehicle. The kinematics and dynamics of (Muir 88) are not included. Results of simulated control system errors are included.

kinematics (No), dynamics (No), control (Yes), wheel slip (No), dead-reckoning(Yes), traction (No), power consumption (No)

(NCSC 86), no author, Omni-Directional Wheel Design Development Effort, Naval Coastal Systems Center report no. NCSC 2250/035-86, Sept. 1986, 18 pages + 4 appendices.

The primary purpose of the this report is to develop the equations, constraints, and numerical methods for design of omni wheel rollers. However, it also provides an excellent summary of the history of omni wheel and its applications. The basic geometric equations for the rollers are provided in the text, with details given in Appendix B, a computer program implementation in Appendix D, and a users manual in Appendix C. Appendix A, is a 69 page presentation of omni-directional ordnance handling concepts using the omni wheel.

kinematics (Yes), dynamics (No), control (No), wheel slip (No), dead-reckoning(No), traction (No), power consumption (No)

(Rembold 88), U. Rembold, "The Karlsruhe Autonomous Mobile Assembly Robot," IEEE??, 1988, pp. 598-603.

This paper describes a vehicle with 4 omni wheels, 2 robot arms, and numerous sensors. The robot arms are mounted high on the vehicle and are oriented downward. The vehicle is intended to move from place to place and do assembly work on a bench or conveyer, much as a human would. This paper describes a proposed vehicle, not one completed. It deals with high level functions and generic descriptions of the overall design, with no details of engineering. The overall concepts and control structure are well presented and are recommended. The use of dead-reckoning is inferred but not explicit.

kinematics (No), dynamics (No), control (Yes), wheel slip (No), dead-reckoning(No), traction (No), power consumption (No)

(Waldron 85), Mobility and Controllability Characteristics of Mobile Robotic Platforms," ??IEEE, 1985, pp. 237-243.

This is a very general comparison of various means of mobile vehicle suspension/propulsion systems. It is an early paper to recognize the omni wheel's advantage in vehicle controllability. The paper also recognizes the need for a suspension, often ignored in mobile vehicle papers.

kinematics (Some), dynamics (No), control (Some), wheel slip (Some), dead-reckoning(Some), traction (Some), power consumption (No)

(Wampfler89), G. Wampfler, M. Salecker, and J. Wittenburg, "Kinematics, Dynamics, and Control of Omnidirectional Vehicles with Mecanum Wheels," Mechanical Structures and Machines, Vol. 72, No. 2, 1989, pp. 165-177

This paper provides an excellent and complete explanation of the dynamics of an omni wheel including the variation in point of contact and roller speed. An energy (virtual power) method of dynamic analysis is presented for modeling the vehicle dynamics. The small non-linearities of the wheel are given as the explanation of some observed vibrations of omni wheeled vehicles.

kinematics (Yes), dynamics (Yes), control (No), wheel slip (Some), dead-reckoning(No), traction (No), power consumption (No)

COMMERCIAL REFERENCES, GFI

(INTEX 88), Intex Omni-Directional Demonstration Vehicle

An omni-directional test platform was produced by International Texas Industries, Inc. (InTex) and delivered to NCSC in January 1988. The vehicle had four 12 inch wheels of the 0 degree type used by InTex. The GVW is 2000 lb., the empty vehicle weight 800 lb. Powered by 4 12 volt batteries the vehicle could travel 4 mph under joystick control. Overall size is 106" in. long, 50 in. high, and 20 inch high, with 8" ground clearance. The electric drive motors and gearing are adjacent to the wheels. Because the wheels are very narrow, approx. 2.5 in., and the leaf spring suspension stiff, the vehicle is intended for hard, flat surfaces only.

(INTEX), InTex Omni-Directional Wheelchair

ALEXIS is a trade name for a three wheel omni-directional vehicle from International Texas Industries, Inc. (InTex). The wheels are similar to those described in (INTEX88). They provide traction in the direction perpendicular to the axle, but no traction in the direction of the axle. The two front wheels are canted inward at about 25 degrees and the rear wheel axle is along the centerline of the vehicle. In straight forward motion the two front wheels rotate at the same rate and the rear wheel is not rotating. Because only 3 wheels are used, all driven, no suspension is needed to keep all wheels on the ground, and there can be no slip detection based on redundant wheels. The vehicle is obviously intended for smooth floors. The empty vehicle, with approximately 80 lb. of batteries, weighs 277 lb. The range on a single charge is reported to be 25 miles. Control is by joystick mounted on the passenger armrest. The passenger cannot exceed 250 lb. weight.

(MACANUM), the initial manufacturer of omni-wheels and systems

The inventor of omni wheels, Bengt Ilon of Sweden, licensed the technology to a new company, Mecanum Innovation AB, in 1981. This company, located at Umea, Sweden, undertook most of the early applications of the wheel, but always with the intention of supplying wheels, technical support, and sublicenses to other companies who would make vehicles using the wheels. Several of the early applications were for large vehicles that manipulated heavy loads where precise positioning was required. These included (1) a carrier of large vehicle chassis for vehicle assembly, (2) a carrier of large cable drums (17 tons) for use in a cable manufacturing plant, and (3) a carrier of large tire and wheel motor assemblies (6.5 tons) for mining equipment. In each of these cases, the large size of the item to be moved made it important to have a very maneuverable vehicle and one that could be used to precisely position the payload.

Other early applications included wheel chairs and industrial lift trucks. Apparently the first 25 wheelchairs were produce in 1982, Mecanum's literature indicates that most of their wheel are built for high loads and slow speeds. A table of properties follows:

Diameter, Width, Payload Pressure, Forward Speed Rollers

Wheel			Contact Pressure	Forward Speed	Rollers	
Diameter	Width	Payload			No.	Diameter
0.5m	.26 m	2500 kg	940 psi	3 km/hr	8	.108 m
.25		640 kg				
.3		1075 kg				
.4		1940 kg		.75 m/s	8	.852 m
.5		2810 kg				
.6		3675 kg				
.7		4540 kg				
.8		5410 kg				
.9		6275 kg				
1.		7140 kg				
.225	.08	50 kg	160 psi	5 km/hr	12	.033 m (rubber)
.225	.08	125 kg	530 psi	5 km/hr	12	.033 m (polyurethane)

In 1984, Macanum became a subsidiary of Contorta AB, and shortened its name to Mecanum AB.

OTHER REFERENCES

(Grosch92), K.A. Grosch, "Abrasion of Rubber and Its Relation to Tire Wear," Rubber Chemistry and Technology, March-April 1992, pp. 78-106.

(Baker89), C.S.L. Baker, I.R. Gelling, and I.R. Wallace, Advances in Natural Rubber for Tires: Compounding for Improved Wear," Elastomerics, July 1989, pp. 20-25.